PHRENIC NERVE INJURIES. REPORT OF A CASE. ANATOMICAL AND EXPERIMENTAL RESEARCHES, AND CRITICAL REVIEW OF THE LITERATURE.*

BY W. E. SCHROEDER, M.D.,
ASSOCIATE PROFESSOR OF SURGERY, NORTHWESTERN UNIVERSITY MEDICAL SCHOOL; SURGEON TO THE WESLEY, PROVIDENT, AND COOK COUNTY HOSPITALS.

WITH

ANATOMICAL OBSERVATIONS ON THE INNERVATION OF THE DIAPHRAGM.

BY F. R. GREEN, A.M., M.D.,
ASSISTANT DEMONSTRATOR OF ANATOMY, NORTHWESTERN UNIVERSITY.

IN a careful examination of the literature on this subject, one finds that most authorities agree that a division of the phrenic nerve or any injury to it is fatal, or certainly very dangerous. I was led to doubt the accuracy of this conclusion, first, by a case of paralysis of the right half of the diaphragm, complicated by a diaphragmatic hernia following an anterior poliomyelitis which I saw in 1892; secondly, by Dr. Murphy's[1] nitrogen gas method of collapsing one lung for tuberculosis; and thirdly, by cases of recovery from surgical pneumothorax, which made me think that the worst that could happen in injury to the phrenic nerve would be a paralysis of one-half of the diaphragm leading to a partial collapse of one lung only.

My skepticism led me to take liberties with the nerve, so that recently I have pinched it systematically every time it has been exposed during a tubercular gland operation, after Fenger's[1] method, and when, during an operation for a tumor of the neck, it was found impossible to remove it without dividing the nerve, I did so unhesitatingly.

I am indebted to Dr. J. Eskridge for this interesting case. It was operated upon at the Provident Hospital, August 30, 1900.

The patient was a widower, white, aged sixty-two years; American, an upholsterer by occupation.

The family history was good, with the exception that two cousins on the mother's side died of cancer of the uterus, and two sisters of heart disease. Father died of pneumonia at the age of eighty-seven.

Patient had been a heavy whiskey drinker until nine years ago, and he still smokes and chews a great deal. He had the usual diseases of childhood, but no others. Twelve years ago his lower jaw was fractured in a railway accident, and eight years ago he was cut in the right supraorbital region by an ax, which resulted in a paresis of the orbicularis palpebrarum muscle. There were no congenital deformities.

The present trouble began nine years ago, when the patient noticed a tumor on the left side of the neck about as large as a hazelnut, but painless. This increased in size very slowly during the first four years, at the end of which time it was about as large as a walnut and painful upon pressure. During the last five years the tumor has grown somewhat more rapidly and has become more painful, and the pain has been constant during the last year.

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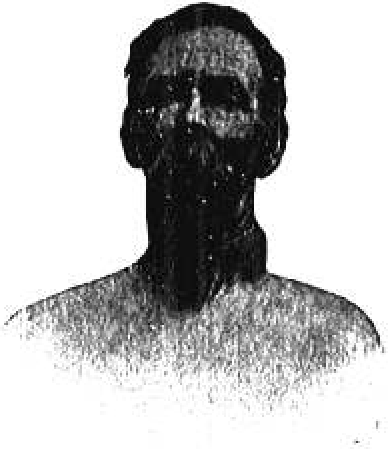
* Read before the Chicago Medical Society, March 18, 1901.

The tumor is situated on the left side of the neck immediately behind the sternocleidomastoid muscle and partly covered by it. (See Fig. 1.) It begins three-fourths of an inch above the clavicle and extends upward two and one-half inches. It is two and one-half inches long in the long diameter, which is parallel with the long axis of the body; its inner margin lies one inch from the left border of the trachea. The skin covering the tumor is normal and freely movable. There are no large vessels to be seen. The tumor feels hard, and is so firmly attached deep down that it cannot be moved. No fluctuation, pulsation, or bruit. No enlarged glands. Aspiration shows, macroscopically, bright red blood in considerable quantity; microscopically, nothing but blood-corpuscles, neither epithelial nor other cells being found. No pressure symptoms.

FIG. 1.



Before operation.

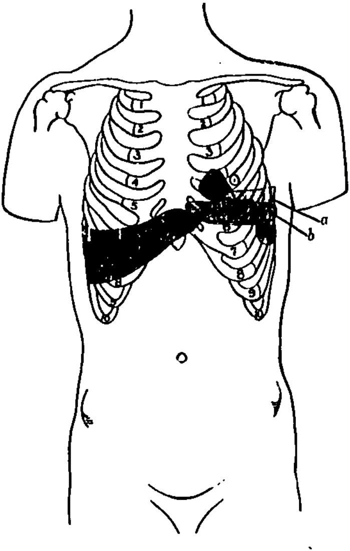
The physical examination of the patient resulted as follows:

Body well nourished; weight, 160 pounds; no recent loss in weight; no abnormality of skin or glandular system. Pulse, temperature, and respiration normal; appetite good; walls of arteries soft; no symptoms of pressure on sympathetic nerves. Paresis of orbicularis palpebrarum due to old injury. Heart and lungs normal. Special attention was paid to the lungs and the position of the diaphragm. Liver, spleen, etc., normal. Urine and blood count normal. Patient was prepared for operation by usual method.

An incision was made from the posterior edge of sternocleidomastoid muscle one inch below the mastoid process to the clavicle. The external jugular vein was ligated and divided between the ligatures. Continuing the dissection, the sternocleidomastoid muscle was liberated and the spinal accessory nerve found and dissected out to the trapezius muscle.

The tumor came into view and showed a capsule which was not adherent to any great extent to the surrounding tissues, but was firmly attached deep down. It was at once noticed that the phrenic nerve lay over the upper outer part of it and that its lower branch was but slightly visible. The nerve was quite tense, but responded twice when it was pinched. As I believed the tumor to be of a malignant nature, I did not wish to divide it for fear of implanting cells in the wound. Therefore, I tried to dissect the nerve from the tumor, but in doing so the small branch from the fifth cervical ruptured, and soon after the main branch from the fourth cervical did likewise.

FIG. 2.*



Anterior view. a. Relative dulness. b. Absolute dulness.

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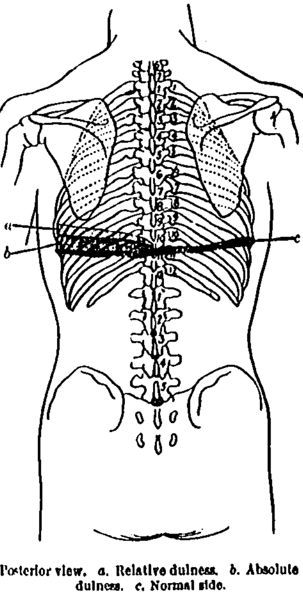
* Figs. 2, 3, and 4: Findings upon percussion after division of nerve. a. Relative dulness, b. Absolute dulness.

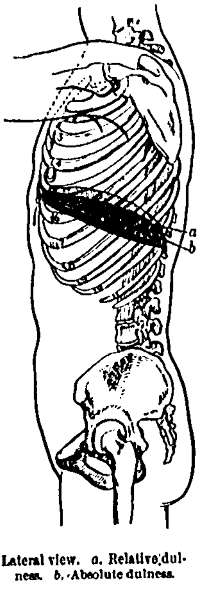
I noticed no material change in the patient excepting an increase in the number of respirations to thirty-two. The tumor was so situated that the upper and main root of the phrenic traversed the upper outer part of it, while the lower root came from underneath. It was firmly attached to the foramen formed by the third and fourth cervical vertebræ, and its removal caused a venous hemorrhage from this point. The fat and various glands were removed from the side of the neck. I followed the phrenic down to the clavicle, injuring the thyroid axis, which produced some hemorrhage. No other branches of the phrenic were found. In trying to unite the divided parts of the nerve, it was impossible to find the little branch from the fifth cervical, but the ragged end of the trunk and that of the fourth root were cut off in order to give uninjured ends, and reunited by means of silk sutures. The nerve was now pinched below the suture, and responded. There was no cough, no singultus, no sneezing, none of the symptoms reported in other cases. The wound was closed in the usual manner. After the patient recovered consciousness, I asked him whether he had any difficulty in breathing or any pain in the region of the diaphragm, but he said he had not. However, the respirations remained more frequent (24 to 30) for four or five days, after which they came down to

FIG. 3.



Posterior view. *a.* Relative dulness. *b.* Absolute dulness. *c.* Normal side.

FIG. 4.



Lateral view. *a.* Relative dulness. *b.* Absolute dulness.

20, and remained so. About eight hours after the operation, percussion showed that the left half of the diaphragm was two and one-half inches above its normal position. An area of the lower portion of the lung, an inch and a half in width, showed relative dulness. (See Figs. 2, 3, and 4.) Litten's sign was absent.

Auscultation over dull area showed vesicular breathing rather distant. Slight abdominal retraction on inspiration. During his three weeks' stay in the hospital the position of the diaphragm remained the same, but the area of relative dulness gradually disappeared and the lung returned to its normal condition. Measurement of the thorax showed right half 44 cm. Deep expiration, 41½ cm. Inspiration, 44½. Left half, 43 cm. Deep expiration, 41½ cm. Inspiration, 43½.

At present the patient is employed as usual, and is suffering no inconvenience from his paralysis.

Macroscopical Examination. The tumor is solid but very vascular. It is two inches in its long diameter and an inch and three-fourths in its transverse diameter. Upon cutting the tumor in half the interior presented a solid consistency, but many large vessels were to be seen. A few small areas, 1 cm. square, were somewhat softer than the main body of the tumor.

Microscopical Examination. One sees numerous connective tissue fibres around the periphery, forming a well-defined capsule, and many areas of leucocytes around which there seems to be young connective tissue. In the centre of the tumor there is a hemorrhage into the tissue. This is very recent, and is probably due to the puncture made by the aspiratory syringe. There are many large and small bloodvessels, but no new ones to be seen. Leucocytes are grouped at various places, resembling an inflammatory process. I believe the tumor to be a fibroma and not, as was thought from the clinical evidence, a fibro-sarcoma.

Experimental Researches.

1. *Upon the Human Subject.* As before stated, in all recent operations for tubercular glands, I have searched for the phrenic nerve and pinched it below the lower root, with the following results: Each time the corresponding side of the diaphragm contracted, producing a sudden and decided abdominal rising immediately below the costal arch. This has been done in eighteen cases, ten right and eight left. In two cases, one right and one left, there was some pain in the region of the corresponding half of the diaphragm, which subsided in each instance before the end of forty-eight hours. The symptoms commonly ascribed to irritation of the phrenic, *i. e.*, sneezing, coughing, and hiccoughing, were not observed in a *single instance.*

2. *Upon Dogs.* The animal experiments have been made upon dogs only, because they resemble man in their type of respiration, which is costo-abdominal. The method of conducting the experiments has been as follows: The circumference of the thorax was taken at the tip of the ensiform cartilage, and again from one to two and one-half inches above it. The number of respirations per minute were recorded

before and after division of the nerves, and the change in type of respiration noted. Ether was the anæsthetic chosen. The usual antiseptic precautions were observed. After exposing the nerve the interrupted electrical current was applied, and then the nerve was pinched with an artery forceps. The nerve was now either evulsed or resected. Later in this work I weighed the animals before the operation and each week thereafter.

Post-mortems were conducted from one week to four months after the division of nerves. For this purpose in most cases the dogs were deeply anæsthetized with chloroform, the thorax opened, the nerves found and stimulated with the electrical current. The various phenomena were observed, and specimens and drawings made. For the details of these experiments see Table I.

It may not be amiss to state here that before obtaining the results shown in this table, there were eight animals that died, but all of these can be accounted for without detracting in the slightest way from the above results. At first I evulsed the nerve, tearing out from three to five inches of it. Out of four cases only two survived. (See Table I., Cases 1 and 2.) Post-mortems of the two that died showed in one case of double evulsion a double pneumothorax and in the other a pneumopyothorax. In the latter case, I heard the rush of air into the pleural cavity, and, infection occurring, the animal died. Evulsion of the nerve lacerates the pleura, and with an infection is liable to result in death from pneumopyothorax; therefore, I abandoned this method of removing the nerve and resorted to resection outside of the pleura, removing as much of the nerve as was possible in each case.

A third animal died from the anæsthetic before any incision had been made.

Five died as a result of experiments with chloretone as an anæsthetic. These animals were given two-tenths of a gramme per kilo, and operations were begun two hours later. They were not completely under, so they were given two-tenths more per kilo, and operations begun after another hour. By this time they were profoundly anæsthetized, but none of them recovered consciousness. They slept from two to four days, when they died.

Weight. The first seven were not weighed, but my observations would lead me to state that the first week or two they lost in weight, after which they gained and again came back to their normal condition. In the last three it will be seen that they lost in weight for the first week, but came back to normal or nearly so. The loss was not great in any instance.

Measurements. It will be seen that in the single division there was an increased thoracic expansion and usually a slight abdominal retraction, which were more evident on the divided side than on the normal side.

TABLE I.

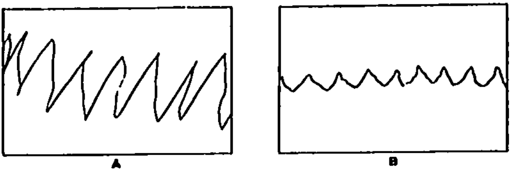
No.	Date of operation.	Sex, size, and weight.	Measurements in inches.								Respiration: frequency and type.		Stimulation of nerve before division.	
			Before operation.				After operation.							
			At ensiform.		Above.		At ensiform.		Above.					
	1900		Exp.	Insp.	Exp.	Insp.	Exp.	Insp.	Exp.	Insp.	Before division.	After division.	Electrical current.	Pinching.
1	Oct. 24	F. small,	15	15½	15½	16	15	15½	15½	16¼	All dogs costo-abdominal type. 24	Costal, abdominal retraction slight. 35	Tetanic contract'n.	Short well-defined contract'ns
2	Nov. 5	M. large,	25¼	26	26¼	27½	25¼	26½	26¼	27	19	Pronounced costal, inverted. 30	Tetanic contract'n.	Short well-defined contract'ns
3	Nov. 24	M. medi'm	21	21¼	22	22¼	21	21¼	22	22½	23	Increased costal, abdomen almost passive; no pronounced retract'n. 27	Tetanic contract'n.	Short well-defined contract'ns
4	Dec. 3	F. small,	14	14½	15	15¼	14	14¼	15	15½	26	Decided & somewhat labored costal; inverted. 36	Tetanic contract'n.	Short well-defined contract'ns
5	Dec. 3	M. small,	21	21¼	22	22¼	21	21½	22	22½	20	Costal, slight retraction only. 24	Tetanic contract'n.	Short well-defined contract'ns
6	Dec. 7	M. small,	20	20¼	20½	20¼	20	20½	20½	21	Costal, slight retraction only. 27	Costal, slight retraction only. 24	Tetanic contract'n; contr. of left leg also.	Short well-defined contract'ns
7	1901 Jan. 23	M. large, 50 lbs. Feb. 12 51 lbs. Feb. 19 51 lbs.	30	30½	...	...	30½	31½	...	...	25	30	Tetanic contract'n.	Short well-defined contract'ns
8	Jan. 23	M. small, 12 lbs. Feb. 12 10 lbs. Feb. 19 11 lbs.	13½	13¼	...	...	13½	13½	...	...	44	Costal, some abdominal retract'n. 40	Tetanic contract'n.	Short well-defined contract'ns
9	Jan. 23	M. medi'm 25 lbs. Feb. 12 24 lbs. Feb. 19 24 lbs.	19	19½	...	...	19	19¼	...	...	24	Breathing only slightly altered. 26	Not pronounced	Not pronounced
10	Jan. 23	M. small, 15 lbs. Feb. 12 12 lbs. Feb. 19 15½ lbs.	15	15½	...	...	15	15¼	...	...	30	Costal, but not pronounced. 32	Tetanic contract'n.	Short contract'ns

TABLE I.—*Continued.*

Division of nerve: right, left, both.	Electrical stimulation before death.	Preliminary to postmortem.	Postmortem findings. Remarks.
Left, evulsion 5 inches.	Tetanic contraction of right, none of left.	Nov. 14, etherized; an incision was made below ensiform through abdominal wall revealing active contraction of r. half of diaph. and passive of left half; kymographic tracing was taken. See Fig. 5.	Nov. 14. Some atrophy of left half of diaph. crossing the median line; no regeneration of left nerve. Dog was six weeks pregnant; uterus contained five embryos; well nourished.
Both, evulsion right 3 in. left 3¼ "	April 16. Chloroform was given, thorax was opened, and left nerve found and stimulated; left half of diaphragm contracted slightly, showing partial regeneration; no reaction of right nerve.	Inverted type of respiration	Marked atrophy of diaphragm, excepting at costal margin; partial arrest of development of abdomen and its contents; no hernia of diaph. Exercised the dog violently Dec. 28, 1900, and Jan. 15, 1901; he did not seem to suffer from labored respiration; still inverted type of respiration; he had been infected.
Right, resection 1 inch.	Jan. 17, 1901. Dog was shot and current applied immediately; no reaction of right nerve; normal contraction of left side.	Just before killing the dog, measurements at ensiform on expiration, 21 in.; on inspiration, 21¾ in.; 2¼ in. above ensiform, on expiration, 22 in.; on inspiration, 22½ in.	Atrophy of right half of diaphragm, which was thin, yellow, semi-transparent; a normal zone ¼ inch wide was formed at the periphery; right nerve had regenerated, but the right half of diaphragm did not respond to stimulation.
Both, resection 1½ inch.	No reaction.	....	Dec. 17. Both nerves show some proximal regeneration; atrophy of diaphragm not very decided, because only 14 days passed between the division and post-mortem.
Right, resection 1½ inch.	No reaction; left normal.	Measurements before killing animal: ensiform, expiration, 21 in.; inspiration, 21¼ in.	Dec. 15. Some atrophy of diaphragm.
Left, resection 1½ inch.	Left reaction; right reaction.	Measurements at ensiform, expiration, 21½ in.; inspiration, 21 in.	Dec. 14, *i. e.*, 7 days after operation, slight atrophy of left half of diaphragm only.
Both, resection 1½ inch.	No reaction on either side.	....	Feb. 26, 1901. Very decided atrophy of both sides; right side, costal margin, one finds an area which is not atrophic, because it receives a nerve from intercostals. Fig. 6. Costal margin not atrophied.
Left, resection 1 inch.	No reaction of left; reaction of right.	....	Feb. 19, 1901. Atrophy of left half of diaphragm; none of right. Fig. 7.
Both, upper two roots found only.	Reaction of both sides in thorax.	....	March 9, 1901. V-shaped portion of diaphragm at ensiform cartilage is atrophied, while the remaining portion is normal. Fig. 8.
Right, resection 1 inch.	Reaction in left; none in right.	....	Mar. 9, 1901. Atrophy of right half of diaphragm, excepting one centimetre of costal margin.

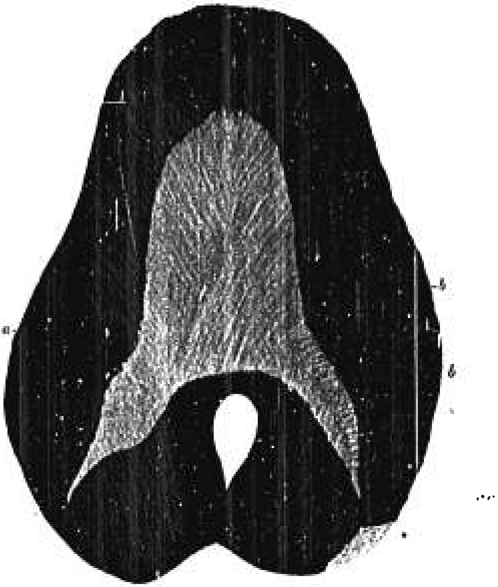
In the double divided cases there occurred an inverted type of respiration, *i. e.*, decided abdominal retraction on inspiration, and increased thoracic expansion due to action of accessory respiratory muscles.

Fig. 5.



a. Excursion of right half of diaphragm. *b.* Passive movement of left or paralyzed half.

Fig. 6.



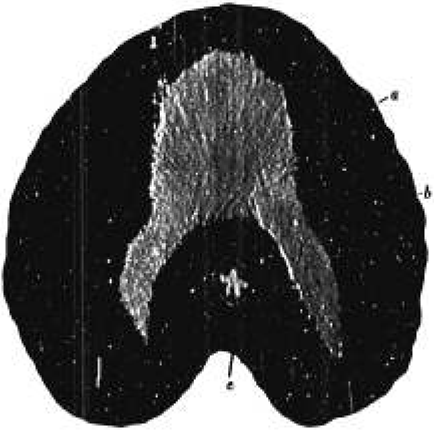
Resection of both phrenic nerves. Dog No. 7. *a.* Normal area. *b.* Non-atrophied margin.

In Case 9, as the upper branches *only* were divided, the animal did not suffer much of a change because the lower branches supply by far the greater part of the diaphragm. (See Fig. 8.)

Electrical Stimulation. In all cases I used the induced current after the Du Bois Raymond method,[3] always with a positive result, *i. e.*, tetanic contraction before division and no reaction after the fourteenth day. In Case 6 the animal was killed only seven days after division, and on stimulation there was a slow, feeble contraction, showing either that the nerve was not yet entirely degenerated or that the atrophy of the diaphragm was not yet complete. In Case 9 the current produced a contraction of diaphragm supplied by lower root. (See Fig. 8, *b b*.)

Excursions of Diaphragm. In dog 1, I opened the abdomen in the median line immediately below the ensiform cartilage and inserted a glass rod, pushing it against first one side of the diaphragm and then the other, taking a kymographic tracing (see Fig. 5), with the result that the right half contracted normally, producing a rise one-half inch in height on inspiration and corresponding depression on expiration. The left half produced a very small rise, one-eighth inch, representing the influence of the contractions of the right side. There was no contraction of the left half. In other animals, I observed the same phenomena, *i. e.*, that the paralyzed side was passive and only acted upon by the contractions of the normal side.

FIG. 7.



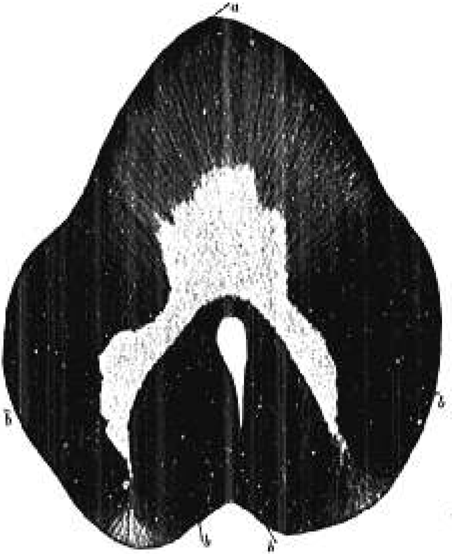
Resection of left phrenic nerve. Dog No. 8. *a*. Non-atrophied margin. *b*. Atrophic area. *c*. Œsophagus.

Symptoms. The diaphragm becomes relaxed after the division of the nerve and arches up into the thorax. The type of respiration becomes increased costal when one nerve only is divided, and inverted when both nerves are divided. The accessory respiratory muscles become very active.

There was no sneezing or coughing in any of the animals. In one case of double division the respiration became labored, but it remained so for two or three days only.

The Post-mortem Findings. Macroscopical. In the cases where the dog was killed from seven to fourteen days after division the atrophy was not very great and the color was reddish-yellow. In cases where a long time had elapsed between the operation and the post-mortem, the atrophy was very decided, the paralyzed part was thin and flabby, the diaphragm was pale yellow, and in some of the older cases translucent. In all cases there remained a margin from one-quarter to three-eighths of an inch wide at the costal border, which retained its normal color and thickness. This margin is probably supplied from the intercostal. (See Figs. 2, 3, and 4.) Again, in the specimen taken from dog 7 (Fig. 6, *a*), it will be seen that there remains a relatively

FIG. 8.



Resection of upper roots. Dog No. 9. *a*. V-shaped atrophic area. *b*, *b*. Normal area. Crura.

normal area on the right side, which was probably supplied by a long branch from the intercostal nerve. In all three figures there is a normal area at the crura. These areas evidently receive an independent nerve supply.

In Fig. 8, where the root coming from the upper branch has been divided (dog No. 9), there is a V-shaped area with its apex toward the sternum extending a distance of two and three-quarter inches on each side toward the spine. This is evidently supplied by the upper branches, the lower branch supplying nearly all of the remaining portion of the diaphragm. In dog No. 3, although the nerve had regenerated after fifty-four days, there was no electrical reaction because of atrophy of the diaphragm.

There is very little available literature upon the experimental work on this subject. Sir Astley Cooper[4] reports having experimented by putting a ligature on the phrenic nerve of a rabbit. The animal suffered from labored respiration and died twenty minutes later. Postmortem showed that the nerve had been cut.

Henocque and Eloy[5] reported some experiments in 1883.

Billard and Cavalie,[6] in 1898, reported on the sequelæ of section of both phrenics in the dog.

REVIEW OF LITERATURE. The literature on this subject is very meagre and confusing, and the conclusions reached by various writers are often diametrically opposite. Thus Gross[7] says: "The division of the phrenic nerve is nearly instantaneously mortal."

Erichsen,[8] in his eighth edition, says: "The division of the respiratory nerves on one side only would, in all probability, be fatal in man by interfering with the proper performance of the respiratory act;" but in his tenth edition[9] he modifies his conclusion, and says: "Division of the phrenic nerve would necessarily, by interfering with respiratory movements, induce a tendency to congestion and inflammation of the lungs; and although such an accident must be a very rare one in cases of ligation of subclavian for axillary aneurism, yet it undoubtedly has occurred as I have myself witnessed in one case."

Ranney[10] says: "Since the phrenic nerve arises in the upper cervical region, any lesion of it will cause respiration to be interfered with and create dyspnœa and hiccough; but respiration will not be arrested, since the pneumogastric nerves continue to excite it, and the auxiliary muscles can expand the chest without the action of the diaphragm. Should the lesion be a surgical one, the respiratory centre of the medulla may be affected and death take place from asphyxia, but I do not think such a result can be explained as a simple effect of paralysis of the phrenic nerves alone."

Hueter-Lossen[11] says: "Paralysis of one-half of the diaphragm puts life in immediate danger. This is evident not only from observation of injuries to the phrenic itself, which are rare, but from injuries to the roots of the nerves in the spinal cord, which determine practically always a fatal termination. These latter may be produced by injuries from the fourth cervical vertebra down, or by degenerative processes spreading from below upward. They are always indicated by paralysis of this principal muscle of respiration, the accessory muscles having been already more or less paralyzed, probably completely. Diaphragmatic paralysis is always easy to determine, since by it alone is inspiration performed under ordinary circumstances."

Diebol[12] calls attention "to the property possessed by nerves and vessels of resisting the encroachments of tumors, just as Langenbeck[13] had much earlier pointed out in his well-known *Beiträge z. Chir. Path. der Venen*. This is fortunate, since the vagus and phrenic nerves remain apparently uncompromised by a degree of pressure which, *a priori*, it would hardly seem as if they could resist. They permit, moreover, considerable displacement without interference of function."

Brodie[14] says: "If the function of the cord be interrupted above origin of the phrenic nerves, respiration is immediately suspended, and instantaneous death ensues."

Park[15] says: "Cases of unilateral division of the phrenic, or of injury to the course of the phrenic—as, for example, in fractures of the cervical vertebræ—indicate that paralysis of the diaphragm, or at least of one-half of it, puts the patient in immediate danger of life, and also compels the other accessory inspiratory muscles to do an enormous amount of compensatory work."

In a later work Park[16] says: "The section of the phrenic and pneumogastric nerves on one side only is accompanied by respiratory and circulatory irregularities; they are not necessarily fatal, but it is a most serious complication."

Tillmann[17] says: "In case of complete paralysis of the phrenic nerves on both sides, death results immediately from paralysis of respiration, as has been experimentally demonstrated upon animals. Irritation of the phrenic nerve causes continuous coughing and hiccoughing in consequence of contraction of the diaphragm."

Later on he says:[18] "After injuries of the subscapular nerve, reflex spasm of the phrenic nerve is sometimes observed with singultus, dyspnœa, and girdle pains."

Gowers[19] says: "If one nerve only is affected, the diaphragm does not descend on that side, but the movements of the other side lessen the resulting defect of movement, and it can then be detected only by close observation. The loss of the action of the diaphragm has little effect on the respiratory functions while the patient is at rest, but dyspnœa is said to be readily produced by exertion; the breathing then becomes quick and the voice feeble."

Rose[10] and Carless say: "Phrenic nerve division may cause instant death by paralysis of the diaphragm, although where but one nerve is divided the patient can survive. Irritation of the nerve gives rise to spasmodic cough or hiccough."

Medical men have not felt nearly so alarmed at paralysis of the diaphragm as have the surgeons, possibly because the lesion in medical cases comes on slowly, and in this manner patients may adapt themselves to new conditions with less danger. Thus Bernhardt[11] says: "The prognosis in paralysis of the phrenic nerves and diaphragm is doubtful, to say the least; but, as Duchenne[12] has shown, the respiration does not suffer much so long as the patient is quiet because of the action of the accessory muscles, but as one may readily understand, bronchitis and other simple diseases of the respiratory organs become serious in such cases."

Many other statements equally diverse in conclusion may be found in the literature.

TABLE II.

Case.	Surgeon.	Year.	Nature of Injury.	Nerves.	Result.
1	Schürmayer,	1847	Stab wound.	Right.	Death in few minutes.
2	Beck,	1848	Bullet wound.	Left.	Death on fifth day.
3	Bardeleben,	1882	Unknown.	......	Death in two hours.
4	Erichsen,	1881	Division while ligating subclavian artery.	......	Death in few days.
5	Mackenzie,	1891	Rupture from fall.	Right.	Death immediate.
6	Schroeder,	1900	Division during operation.	Left.	Recovery.

I have been able to find only five cases of actual injury to the phrenic nerve (see Table II.), though there are several others which have been commonly reported as such which, when traced to the original documents, have been found to be erroneous. In some of these the injury to the phrenic nerve is only an assumption on the part of some later writer, who, noticing that the symptoms commonly described as caused by such an injury were present, has inferred that the phrenic nerve must certainly have been injured, while in still others the surgeon has reported an injury to the pneumogostric, but has been cited by others as having injured the phrenic.

The first of the cases of actual injury to the phrenic nerve is that of Schürmayer.[13]

Patient was a male, aged twenty-six years, previously well. He was wounded October 16, 1847, by a knife, which penetrated the right side of the neck. The wound began one and one-half inches above the acromial end of the clavicle, passed downward, forward, and inward, ending at the sternal end of the clavicle. In its course the knife-blade

> injured the trapezius, splenius capitis, levator scapula, scaleni, and sternocleidomastoid muscles, the fifth cervical, phrenic and branches of the sympathetic plexuses, and the internal jugular vein. Immediately following the injury the patient complained of lameness of the right arm, which hung loosely at his side. Hemorrhage was quite severe. He left the room, going into the kitchen, and after a few complaining words, collapsed and died in the course of a few minutes.
>
> The post-mortem, which was very complete, showed anæmia of vessels in skull and brain, but unusual fulness of vessels in lungs. There were numerous adhesions of the pleura.

Schürmayer says that death was not due to hemorrhage, because of the negative post-mortem findings, but that it was due to division of the phrenic nerve complicated by these numerous adhesions of the lung to the pleura. He believes it probable that cases of unilateral division may recover, and refers to Larrey, but declares that, in the sense of the law, death in this case was due to injury of the phrenic nerve.

The second case, reported by Beck,[12] was that of a young man who was shot in the neck during a duel. Upon examination it was found that the bullet had entered two fingers' breadths above the left clavicle at the posterior border of the sternocleidomastoid, and came out on the opposite side at the junction of the upper with the middle third of the neck, anterior to the sternocleidomastoid muscle. The respiration was slow and difficult, pulse weak, pupil of the left eye contracted. On the fifth day he breathed nine to seventeen times per minute. Laryngotomy was performed, during which operation the patient died. Beck performed the post-mortem and found the following: The bullet had contused the left phrenic nerve so that there was an extravasation of blood in the neurilemma, had passed back of the left carotid between the vagus and sympathetic nerves, lacerating the cervical ganglia of the latter, and had then passed through the œsophagus and lacerated the right arytenoid cartilage and the right descendens noni.

In conclusion, Beck states that as the injury to the phrenic nerve resulted in a partial loss of the function of the diaphragm, it certainly complicated a condition.

In some way this case has been attributed to Stromeyer,[13] who reported it about 1870, at which time he also reported another case of contusion of the phrenic and brachial plexus with rapid recovery.

In 1882 Bardeleben[14] reported a case of division of the pneumogastric and phrenic nerve with no immediate symptoms, but soon the patient's respiration became slow and difficult, and he died in two hours.

In 1884 Erichsen[8] says: "In a case with which I am acquainted, where the phrenic nerve was divided during a ligation of the subclavian artery, death resulted in a few days from congestion of the lungs."

In 1891 Mackenzie[15] reports a case of rupture of the right phrenic nerve with instant death.

In reviewing these five cases it will be seen that in only one, that is the last one, was there an injury to the phrenic nerve alone, while in all the others there were sufficient injuries to other important structures to account for the unfavorable termination.

In considering the other cases, *i. e.*, those commonly but erroneously considered as phrenic nerve injuries, there are two which deserve special mention, as they have been so widely and frequently quoted, *i. e.*, Bransby Cooper's[11] and Hutin's.[12]

It has been commonly reported that Bransby Cooper, in 1841, while ligating a subclavian artery for aneurism, included the phrenic nerve in the ligature. In reviewing this case carefully, it was found that Cooper states that the patient developed a cough, which persisted more or less violently until his death on the fifteenth day. But the post-mortem, which was incomplete and was done fifteen hours later, showed the phrenic nerve "*in situ* and glued down to the scalenus muscle." Aspiration showed pus in the pleural cavity on the same side.

Hutin's case was operated on in October, 1841; for wound in the axilla. He got up on the sixth day, after which he began to cough. At this time the wound was fetid. On the ninth day he had a slight hemorrhage, and on the tenth day, for fear of a great hemorrhage, Hutin ligated the subclavian artery, but the patient died ten hours later.

Post-mortem showed the artery intact, and Hutin specifically states that no nerves or other important structures were found in the ligature.

Of five cases to which Park[13] refers as injuries of the phrenic nerve, four, three of Demme's[14] and one of Riedel's,[15] were found to be injuries of the pneumogastric, while in the fifth (Hofmokl's)[16] the injury was in the cervical plexus below the phrenic nerve.

Referring to the case which came under my observation, one might infer that as the tumor was of slow growth, the gradual pressure upon the nerve had produced a slow paralysis of the diaphragm; but in answer to this, I can say, as Langenbeck[17] and Diebel[18] have previously shown, that these nerves withstand pressure without much disturbance; secondly, upon pinching the nerve four different times, the epigastric region on the same side showed a sharp sudden rise each time, showing that there had been no paralysis; lastly, the physical examination before the operation showed the diaphragm to be in its normal position and the lungs absolutely normal.

ANATOMICAL RESEARCHES. The subject of the innervation of the diaphragm will be considered under two heads.

1. Innervation from the phrenic nerve. 2. Innervation from any other source.

Under the second heading will be considered: 1. Innervation from the intercostal. 2. Innervation from the sympathetic. 3. Innervation from the pneumogastric.

Innervation from the phrenic nerve. The phrenic nerve or the internal respiratory nerve of Bell is the most conspicuous nerve supplying the diaphragm. It has, by most anatomists, both descriptive and comparative, been considered the sole nerve supply to this muscle. This nerve will be considered under three heads.

1. Its origin: (*a*) spinal or deep; (*b*) cervical or superficial. 2. Course and relations. 3. Distribution.

Spinal Origin. Marinesco,[31] in 1898, described a nerve centre in the spinal cord of dogs and rabbits, from which proceeds the nerve fibres of the phrenic nerve.

He describes it as a "group of cells which occupy an intermediate position between the anterior internal and anterior external groups of the anterior horn, extending from the level of the lower border of the fourth cervical vertebra to the lower border of the sixth cervical in dogs, and a little lower down in rabbits. In rabbits these cells are not distinguishable from other cells. In the dog they are smaller and their processes less marked."

Sano,[32] in the same year (1898), described a motor nucleus for the phrenic nerve in man, located in the centre of the anterior horn, extending from the middle of the third to the sixth segment. Sensory neurons originate, he says, in ganglia in the posterior roots of the third, fourth, fifth, and sixth cervical nerves.

Superficial Origin. Most of our standard English anatomical authorities give the origin as principally from the fourth cervical, with accessory branches from the third or fifth, or both, but with no figures as to relative frequency of different origins or the proportion in which different roots are found.

Luschka,[33] in 1853, published the results of thirty-two dissections of the phrenic roots, showing the following results:

Number originating from the 4th alone	12	37.5	per cent.
" " " 4th and 5th	7	21.87	"
" " " 3d, 4th, and 5th	7	21.87	"
" " " 3d and 4th	6	18.75	"

Brook,[34] of Dublin, in 1887, reviewed Luschka's work and reported sixteen dissections as follows:

Number originating from the 4th alone	4	25	per cent.
" " " 4th and 5th	9	56.25	"
" " " 3d, 4th, and 5th	3	19	"
" " " 3d and 4th	0		

In the past four months, from observations made in the dissecting-room of the Northwestern University Medical School I have obtained the following results:

Number of cases observed	52
" " on the right side	25
" " on the left side	27

These nerves had the following origin :

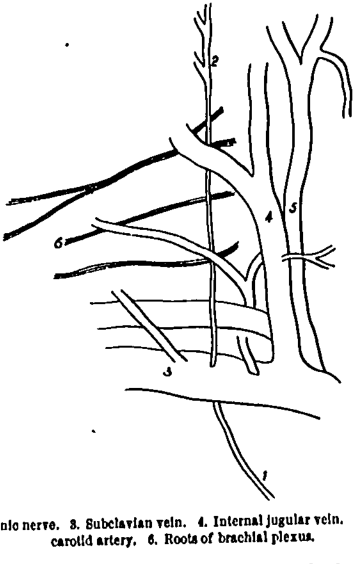
Number of cases from the 4th alone	9	17.3 per cent.
" " " 4th and 5th	21	40 38 "
" " " 3d, 4th and 5th	13	25 "
" " " 3d and 4th	9	17.3 "

These various results when tabulated show as follows :

	No. of cases.	*4th only.*		*4th and 5th.*		*3d, 4th, and 5th.*		*3d and 4th.*	
Luschka,	32	12	37.5 per ct.	7	21.87 per ct.	7	21.87 per ct.	6	18.75 per ct.
Brook,	16	4	25 "	9	56.25 "	3	19 "	0	0 "
Green,	52	9	17.3 "	21	40.38 "	13	25 "	9	17.3 "
Total,	100	25	25 per ct.	37	37 per ct.	23	23 per ct.	15	15 per ct.

Number of roots. When there is a single root it is from the fourth cervical. This occurred in 25 cases in 100. When there are two roots they are from either the third and fourth or the fourth and fifth. In 52 cases the nerve had two roots.

FIG. 9.



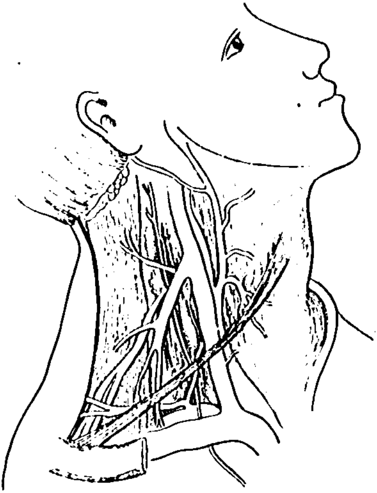
1, 2. Phrenic nerve. 3. Subclavian vein. 4. Internal jugular vein. 5. Common carotid artery. 6. Roots of brachial plexus.

In 23 cases the nerve had three roots of origin, viz., from the third, fourth and fifth.

Course. The nerve seems surprisingly constant in its course. It is generally as described in the standard text-books, with few variations. One or two relations, however, are worthy of notice.

To the subclavian vein. I have noted this relation in 51 cases. In 26 cases on the left side, the nerve passed behind the vein in all. In 25 cases on the right side, the nerve passed behind the vein in 22, in front in 2, and in the remaining case passed through the vein. (See Figs. 9 and 10.) Of this peculiar anomaly I have been able to find but one similar case reported in the literature. In Virchow's *Archiv* for 1872, Von Wenzel Gruber,[37] of St. Petersburg, reported a case of the left subclavian vein dividing and reuniting so as to form "an island four millimetres long and two millimetres wide, through which passed the left phrenic nerve." Henocque and Eloy, in their article on the phrenic nerve, in the *Dictionnaire Encyclopedique des Med. Scien.*, say that Louget has observed a similar case, but I was not able to find any description of it in his work on the *Nervous System*.

FIG. 10.



Course of phrenic (right) in neck, showing relations to adjacent structures.

Fawcett,[38] Barton,[39] Walsham,[40] Hunter,[41] and Turner[42] have reported one case each of the phrenic passing in front of the subclavian vein. Of these five cases, three were on the left side and two on the right. It is probably comparatively common.

I found this anomaly present twice in 51 cases, or nearly 4 per cent. It seems worthy of note on account of its relation to the clavicle. When lying in this anomalous position it is immediately behind the posterior surface of the clavicle, and might be lacerated or divided in fracture of the clavicle or included in the callus.

Relation to the Internal Mammary Artery. At the origin of the artery: This relation was observed 22 times on the left side and 20 times on the right, or 42 times in all. In 22 cases (9 right; 13 left) it was external to the origin of the artery. In 13 cases (6 right; 7 left) it was internal. In 7 cases (5 right; 2 left) the nerve passed directly over the origin of the artery.

Relation of the nerve to the course of the artery. This relation was observed in 32 cases, of which 15 were on the right side and 17 on the left side. On the right side there were 14 cases in which the nerve was internal to the artery and one in which it was external. In 17 cases on the left side, the nerve was internal to the artery in 13 cases and external in 4 cases. In a total of 32 cases observed, then, the nerve lay internal in 27 and external in 5 cases.

Distribution. The main distribution of the nerve is to the diaphragm. Small twigs, varying in number, are sent to the superior vena cava, the pleura, and the pericardium. Luschka has described branches to the right auricle. This observation I have not been able to confirm. The branches in the thorax are small and easily destroyed, hence were not demonstrable in many cases on account of the parts having been disturbed before observations could be made. The branch to the superior vena cava from the right phrenic is very constant, and can, I think, be demonstrated in all cases where the integrity of the parts has been preserved. Branches to the pleura and pericardium vary in number from 1 to 4 to each structure.

The course of the main trunk of the nerve is as generally described, the left phrenic being longer and having a course far to the left over the pericardium. It breaks up into its terminal branches about 3 or 4 cm. above the thoracic surface of the diaphragm. It may remain intact until it pierces the diaphragm and divide in its substance or on its lower surface. In 29 cases in which the point of division was noted, the nerve divided above the diaphragm in 18, and in the substance of the muscle in 11 cases.

The statement made in some of our standard English works on anatomy, that the right phrenic passes through the opening for the inferior vena cava, is not borne out by the observations made. In the great majority of cases the nerve passed through a separate opening a few centimetres in front and to the right of the opening for the vein.

The diaphragmatic branches are from 2 to 6 in number, and are distributed to the lateral and anterior portions of the muscle, dividing and subdividing into fine nerve filaments, and soon losing themselves in the substance of the muscle. The exact areas supplied are as yet undetermined. The single case of a dog observed by Dr. Schroeder, in which section was made of the upper roots of origin of the phrenic, the lower being unimpaired, is the only case of the kind I know of. In this dog post-mortem showed degeneration of the anterior and middle portions of the muscle, with the lateral portion normal. I hope at some future time to make some further observations on the exact distribution of these terminal branches.

In 15 cases the right phrenic perforated, in 12 cases branches were observed below the diaphragm, and in 9 cases it was possible to trace branches to the solar plexus. Two very careful dissections on unusually favorable cases showed branches of distribution as described, viz., to the semilunar ganglion, to the suprarenal and hepatic plexuses. These branches of communication in every case observed came from the innermost terminal branch of the right nerve, which pierced the diaphragm close to the inferior vena cava and ran downward and inward, retroperitoneally, to the semilunar ganglion. Whether the branches of distribution in the abdominal cavity are mainly from the phrenic or the sympathetic, or whether the branch connecting the right phrenic with the solar plexus is an afferent or an efferent branch, is as yet undetermined. In no case were abdominal branches observed on the left side.

The question of decussation of nerve fibres is undetermined, and upon this we have conflicting evidence. Kohnstamm,[4] in his *Studien über den Phrenicuskern*, says: "Innervation of diaphragmatic halves is distinctly bilateral, inasmuch as each phrenic supplies only the same side of the diaphragm and comes only from nucleus of same side, which in the rabbit lies from 6 to 10.4 segments of cord. A crossing of peripheral nerves in the anterior commissure does not occur in the phrenic. Ventral part of diaphragm is supplied by a cranial trunk and dorsal by a caudal trunk."

On the other hand, Henocque and Eloy[5] say: "The peripheral branches of the nerve (phrenic) form a plexus which completes the anastomosis between the two median halves of the diaphragm."

The question of nerve communication between the two median halves of the muscle is most important, but as yet undetermined.

Innervation from the Intercostal Nerves. Luschka,[15] in 1853, published a monograph on the phrenic nerve, in which he says: "The fleshy portion of the diaphragm receives motor filaments from the intercostals from the seventh to the twelfth." Later on, in his *Anatomie des Menschen*,[16] he says, in describing the last two intercostal nerves: "During their course along the last six ribs these nerves supply not only the intercostal muscles, but also, as I have previously described, the costal portion of the diaphragm. These penetrate into the costal digitations of the diaphragm in company with the terminal branches of the arteries, and are usually so fine as to consist of primitive nerve-fibres."

Previous to Luschka, however, Bauer,[45] Meckel,[46] and Valentine had described branches to the diaphragm in man, coming from the lower intercostal nerves. Their exact origin and distribution had not, however, been determined. Their work, however, seems to have been generally overlooked, or, at least, not emphasized. Cavalié,[34] writing in 1896, says: "They are not mentioned in any of our standard authors, except a foot-note in Beauner and Bouchard's *Anatomie*."

Among English authorities also these branches seem to have been overlooked. Quain,[47] in his last edition, refers in a foot-note to Luschka's work in a general way. McClellan[48] simply says that such branches exist. Gerrish and Morris make no mention of them. Gray[49] does not refer to them previous to the thirteenth edition, into which is interpolated the statement that filaments from the intercostals have been traced to the diaphragm. In most comparative anatomics there is no reference to this nerve supply. Chauveau,[50] Mivart,[51] Weldersheim,[52] Wilder and Gage,[53] and Huxley[54] make no mention of it.

In 1888, Pansini,[55] of Naples, described a subdiaphragmatic plexus in rabbits formed by "the phrenic and also branches from the three intercostals." This plexus he subdivides into three: anterior, middle, and posterior plexuses. He also describes numerous ganglia in these plexuses, especially in the posterior one.

In 1896, Cavalié,[34] of Toulouse, published the results of the dissection of six adult human diaphragms, or 12 lateral halves. By dividing the diaphragm in the median line and sawing through the spinal vertebra longitudinally he removed each half of the diaphragm intact, with its costal and vertebral attachments. After macerating the part in a weak solution of nitric acid, he demonstrated diaphragmatic branches from the intercostal nerves, with the following origins:

1. There are no diaphragmatic branches from the sixth intercostal nerve.
2. Branches were observed coming from the eleventh, eighth, and seventh most abundantly, then from the tenth, twelfth, and ninth in the order named, the last being relatively poor in branches.

Course. Diaphragmatic branches arise from the intercostals just as the latter pass over the insertion (costal) of the diaphragm. They either pierce the aponeurosis (of the internal intercostal muscle) or pass through its interstices, and are directed toward the muscular fibres of the diaphragm. They are sometimes alone and sometimes accompanied by the branches of the intercostal vessels. They number 5 or 6 from each intercostal nerve.

Distribution. These diaphragmatic branches from the intercostals supply a narrow margin along the costal border of the diaphragm, varying from 1 to 3 cm. in width. Cavalié was not able to recognize any anastomosis of these fibres with the terminal branches of the phrenic, nor did he observe any of the ganglia described by Pansini.

In later papers, published in 1898, Cavalié and Billard[17] report the results of two series of experiments. By the first[17] they demonstrated the existence of motor fibres in the diaphragmatic branches of the intercostals. In the second series[18] they proved, by physiological experimentation, that the intercostal nerves cannot assume the rôle of the phrenic after division of the phrenic itself.

Stimulation of the peripheral ends of the divided intercostals in the first series of experiments showed visible contractions of an area of about 3 cm. wide in dogs, and of a length about equal extending in the direction of the muscular fibres. Tracings of these contractions were feeble and of slight amplitude. In the second series of experiments the investigators endeavored to ascertain if the intercostal nerves could assume the rôle of the phrenic in innervating the diaphragm after section of the latter nerve. They decided that it could not, although diaphragmatic contractions on stimulating the intercostals were greater in a dog whose phrenic had been cut a month previous than in one where the phrenic had been divided just previous to the experiment. Instead of indicating any vicarious action of the intercostals, however, Dr. Schroeder is of the opinion, from his extended work on dogs, that this is due to a simple hypertrophy of the muscle fibres of the costal margin of the diaphragm following paralysis of all the rest of the muscle, and not in any way an assumption of the function of one nerve by another. This certainly appears more reasonable.

Cavalié's conclusion from his physiological experimentation, then, is that the diaphragmatic branches of the intercostal nerves cannot, in mammals, assume the rôle of the phrenic after division of the latter.

Later, in 1898, Cavalié[19] published the results of an extended series of observations on mammals and birds, with four additional human dissections, confirming his previous observations, and bringing his series of dissections up to twenty lateral halves. His observations on mammals were made on dogs, rabbits, guinea-pigs, and rats, on birds, on the cock, pigeon, sparrowhawk, and duck. His observations on dogs are most interesting, and his description of the various branches of innervation of the diaphragm very minute and accurate, but we can only give his final conclusions:

1. The intercostal nerves send branches to the diaphragm in birds and mammals.

2. In birds and mammals these branches contain motor fibres. They probably do in man.

3. They play a certain rôle in respiration, secondary in importance after the appearance of the phrenic.

4. Birds have no phrenic nerve. The diaphragm is principally supplied by the thoracic nerves which correspond to the intercostals in mammals.

5. As one leaves birds and approaches mammals the rôle of the phrenic becomes more important, and the area supplied by it becomes greater; while the rôle of the intercostals becomes less important, and the area supplied by them becomes smaller.

6. In rabbits, guinea-pigs, and rats the last five intercostals send branches to the diaphragm. In dogs the last seven, especially the eighth, ninth, tenth, and eleventh.

7. In man the last six, especially the seventh, eighth, and eleventh.

8. In dogs the area supplied is the costal margin of the diaphragm for a width of about 3 cm. In a man for a varying width of 1 to 2 cm.

I have reviewed Cavalié's work at length, as he has done the largest amount of work along this line and, so far as I know, his investigations have never been reviewed in English.

Sympathetic Nerve Supply. The innermost branch from the right phrenic communicates with the semilunar ganglion of the solar plexus. I was able to demonstrate this communication but nine times, but found it in all cases where careful dissections were made on undisturbed structures. Whether these nerves are afferent or efferent is still undetermined. In no case did I observe any abdominal branches from the left phrenic.

SUMMARY. Our conclusions may be summed up as follows:

1. From the clinical and experimental data it would seem that the diaphragm is not an essential muscle of respiration.

2. That as the symptoms commonly described as caused by an irritation on the phrenic were uniformly absent not only in the operation, but in all of the experimental work as well, it is safe to infer that they may have been due to something other than a simple injury to the phrenic.

3. That while from an anatomical point of view the diaphragm undoubtedly is enervated by branches from the intercostal nerves, this nerve supply is secondary to the phrenic and is insufficient to carry on the action of the diaphragm after a division of the phrenic.

4. That a division of the phrenic nerve, producing a partial collapse of the lower lobe of the lung on the affected side and an atrophy of one-half of the diaphragm, might predispose to infection of the lung or be followed by a diaphragmatic hernia.

5. That a division of one phrenic nerve in man, resulting in paralysis of one-half of the diaphragm only, is not necessarily fatal.

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